

Direct CP violation of $B \rightarrow l\nu$ in unparticle physics

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We have investigated the effects of unparticles in decays $B \rightarrow l\nu$. It is found that the direct CP violation in the decays, which is zero in SM, can show up due to the CP conserving phase intrinsic in unparticle physics. For $l = \tau$, the direct CP asymmetry can reach 30% for the scalar unparticle contribution, and 100% for the longitudinal vector unparticle contribution under the constraints of $\text{Br}(B \rightarrow \tau\nu)$ and νe elastic scattering. If both unparticle-lepton coupling universality and unparticle-quark coupling universality are assumed the constraint from $\text{Br}(\pi \rightarrow \mu\nu)$ leads that the direct CP violation in $B \rightarrow l\nu$ can only reach at most 8% and 1% for scalar and vector unparticle contributions respectively if $d_{\mathcal{U}} < 2$. If the direct CP violation is observed in the future it would give strong evidence for the existence of unparticle stuff.

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The scale invariant and conformal invariant quantum field theories in two and higher dimensions have been extensively investigated [1]. For example, it was noted that there is an infra-red fixed point in $\text{SU}(N)$ gauge theory with massless fermions if the number of fermion representations $f = \frac{11}{2}N - k$ with $k \ll N$ [2]. They have been widely applied in a number of fields in physics. However, unfortunately, particle physics at the low energy (say, the electro-weak scale) can not be described by scale invariant theories because $[P_\mu, D] = iP_\mu$, where D is the scale transformation generator, leads to that the mass spectrum of scale invariant system is either continuous or massless. Therefore, scale invariant stuff, if it exists, is made of unparticles.

Georgi recently proposed an interesting suggestion to determine experimentally whether unparticle stuff actually exists [3]. Assuming there are interacting two sectors above a high energy scale $M_{\mathcal{U}}$: one is the SM, the other is a nontrivial scale invariant renormalizable quantum field system of scale dimension $d_{\mathcal{U}}$, the non-renormalizable terms due to the interactions between the two sectors exist below $M_{\mathcal{U}}$ and, in the form of operator product, can generally be written as

$$O_{SM}O_{SI}/M_{\mathcal{U}}^n \quad \text{with } n > 0, \quad (1)$$

where O_{SM} and O_{SI} are an operator with dimension d_{SM} built of SM fields and an operator with dimension d_{SI} built of fields in the scale invariant sector respectively. What can we see below a low energy scale Λ which is much smaller than $M_{\mathcal{U}}$? Can we see the effects of the nontrivial scale invariant sector below Λ ? For this purpose Georgi presented to use effective field theory approach. In the effective field theory below Λ the scale invariant operators O_{SI} match onto the unparticle operators and the interactions (1) match onto interactions

of the form

$$\frac{C_U \Lambda^{d_{SI}-d_U}}{M_U^n} O_{SM} O_U \quad (2)$$

where d_U is the scaling dimension of the unparticle operator O_U and C_U is a constant coefficient function.

There are a lot of papers which discuss phenomenological consequences in unparticle physics [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31]. As it is well-known, there are many theoretical models beyond SM. The most important issue is how to discriminate one from the others. For unparticles, there is a distinguishing feature which differs from all other well-known models. That is, there are CP conserving phases in unparticle propagators. Because the phases appear in propagators of unparticles and conserve CP they should act as the strong phases in physics processes. The phases would show up in various processes. An interesting observation by Chen and Geng is to measure the direct CP violation in rare leptonic decays $B \rightarrow l^+ l^-$ [7]. Because the direct CP violation in the decays is zero in SM and all other well-known models, its discovery would give strong evidence for the existence of unparticle stuff. However, from the experimental point of view, it is far away to do the measurements because the branching ratios of rare leptonic B decays have not been determined yet. In contrary, leptonic charged B decays have been observed and the branching ratio in $B^+ \rightarrow \tau^+ \nu_\tau$ has been recently given by the BaBar collaboration [32],

$$\text{Br}(B^+ \rightarrow \tau^+ \nu) = (0.9 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-4} \quad (3)$$

$$< 1.7 \times 10^{-4} \text{ at } 90\% \text{ C.L.}$$

The experimental data of Br of $B^- \rightarrow \tau^- \nu$ by the Belle collaboration is [33]

$$\text{Br}(B^- \rightarrow \tau^- \nu) = (1.79_{-0.49}^{+0.56}(\text{stat.})_{-0.51}^{+0.46}(\text{syst.})) \times 10^{-4}. \quad (4)$$

It is expected to measure the direct CP violation of $B^\pm \rightarrow \tau^\pm \nu_\tau$ in B factories and super B factories [41] in the near future. Because there are no hadronic final states in the leptonic charged B decays and consequently the direct CP violation in the decays is zero in SM and all other well-known models, its discovery would give strong evidence for the existence of the unparticle stuff. In this paper we shall study the phase effects of unparticles in the leptonic charged B decays. We show that the direct CP violation in $B^+ \rightarrow \tau^+ \nu_\tau$ can reach 30% for scalar unparticle contribution, and 100% for longitudinal vector unparticle contribution under the constraints of $\text{Br}(B \rightarrow \tau \nu)$ and νe elastic scattering in the reasonable region of parameters in unparticle physics.

In discussions so far, the unparticle operator O_U is assumed to be the SM singlet. However, it is not unreasonable to assume there are SM non-singlet unparticle operators. It was argued in ref. [34] that for every $\frac{3}{2}N_c < N_f < 3N_c$ there is a non-trivial fixed point in super Yang-Mills theories with the gauge group $SU(N_c)$ and N_f quark flavors in the fundamental representation of the gauge group. Therefore, for this range of N_f , the infrared theory is a non-trivial four dimensional superconformal field theory and the charged scale invariant fields could exist. As pointed out in ref [35], although the results are obtained for supersymmetric field theories, the insights obtained are expected to be also applicable for non-supersymmetric theories, at least at a qualitative level, because the dynamical mechanisms explored are standard to gauge theories. The charged currents in SM would interact with the charged scale invariant fields [34, 36] by exchanging some charged

particles and/or charged scale invariant fields at the high scale. Therefore, we can parameterize the effective couplings of unparticles to the charged leptonic currents as follows.

$$\frac{1}{\Lambda^{d_U-1}} \sum_{i=e,\mu,\tau} C_V^{l_i} \bar{l}_i \gamma_\mu (1 - \gamma_5) \nu_i O_U^\mu + \frac{1}{\Lambda^{d_U}} \sum_{i=e,\mu,\tau} C_S^{l_i} \bar{l}_i \gamma_\mu (1 - \gamma_5) \nu_i \partial^\mu O_U + h.c., \quad (5)$$

where O_U and O_U^μ are scalar and vector operators respectively. In principle the vector and axial-vector couplings may be different and there may be scalar and pseudo-scalar couplings. For simplicity here we assume the above left-handed couplings. Similarly we parameterize the effective couplings of unparticle to the charged quark currents as

$$\frac{1}{\Lambda^{d_U-1}} \sum_{q'=u,c,t,q=d,s,b} C_V^{q'q} \bar{q}' \gamma_\mu (1 - \gamma_5) q O_U^\mu + \frac{1}{\Lambda^{d_U}} \sum_{q'=u,c,t,q=d,s,b} C_S^{q'q} \bar{q}' \gamma_\mu (1 - \gamma_5) q \partial^\mu O_U + h.c. \quad (6)$$

In eqs.(5) and (6), C 's are dimensionless parameters* which have been assumed to be real for simplicity. Recently the direct CP violation in leptonic B decays due to charged unparticle effects is also analyzed by introducing scalar and pseudo-scalar couplings of unparticles to quarks and leptons [37].

Due to the interaction between the charged currents in SM and the charged scale invariant fields which could give a correction to the fixed point of the scale invariant sector, the scale (conformal) invariance of the scale (conformal) invariant sector would be violated. Because the unparticles, which we consider in the paper, are electromagnetically charged, it is expected that breaking of scale (conformal) invariance would be weaker than that for the colored unparticles. As analyzed in refs. [15, 26], even for the SM singlet scalar unparticle the scale invariance would be violated after electroweak symmetry breaking if it couples to Higgs sector, and the scale, at which the conformal invariance is broken by the Higgs vacuum expectation value, depends on the coupling of SM singlet scalar unparticle to Higgs and the conformal window can extend down to the scale of B meson mass if the coupling is small enough (say, smaller than 0.01). We do not have detailed models to describe the scale invariant sector and do not know the details of how the scale invariance is broken. However, we know that arising of the scale invariance breaking must be at a low energy. So we shall parameterize our ignorance with an infra-red cutoff scale μ for the unparticle propagator. That is, we modify the propagators of scalar and vector particles in refs. [4, 5] to

$$\Delta_{O_U} = i \frac{A_{d_U}}{2 \sin(d_U \pi)} (P^2 - \mu^2)^{d_U-2} e^{-i\phi_U}, \Delta_{O_U^\mu} = i \frac{A_{d_U}}{2 \sin(d_U \pi)} \Pi^{\mu\nu} (P^2 - \mu^2)^{d_U-2} e^{-i\phi_U}, \quad (7)$$

where the constant $\phi_U = (d_U - 2)\pi$ and

$$\Pi^{\mu\nu} = -g^{\mu\nu} + P^\mu P^\nu / P^2 \quad (8)$$

if assuming the vector unparticle is transverse, $\partial_\mu O_U^\mu = 0$. As pointed out in ref. [38], the vector unparticle scale dimension $d_U < 2$ is allowed when scale invariance is broken at a scale $\mu \geq 1 \text{ GeV}$. Furthermore, it is shown that the decay into an unparticle has a non-integrable singularity in the decay rate for $d_U < 1$ [3]. Therefore, we shall assume $1 < d_U < 2$ in numerical calculations below.

* Scale factors have been included into the definitions of C 's, e.g., $C_S^l = c_S^l \Lambda_{SI}^d / M_U^n$.

We find the transverse vector unparticle does not contribute to the decay $B^\pm \rightarrow l^\pm \nu$. By a straightforward calculation we obtain the contributions of scalar unparticles to the amplitude in $B^\pm \rightarrow l^\pm \nu$,

$$A^U = f_B C_S^l C_S^{bu} \frac{A_{d_U}}{2 \sin(d_U \pi)} \frac{m_B^{2(d_U-1)}}{\Lambda^{2d_U}} \left(1 - \frac{\mu^2}{m_B^2}\right)^{d_U-2} e^{-i\phi_U} \bar{\nu} \not{P}(1 - \gamma_5) l, \quad (9)$$

where the decay constant f_B is defined as usual,

$$\langle 0 | \bar{b} \gamma_\mu \gamma_5 u | B^+(P) \rangle = -i f_B P_\mu. \quad (10)$$

In eq. (9), A_{d_U} is the normalization factor of phase space for unparticle stuff. For the phenomenological analysis, one can constrain the product $C_S^l C_S^{bu}$, so that besides the infra-red cutoff μ , we have three new parameters: d_U , Λ , $C_S^l C_S^{bu}$. The amplitude in SM is

$$A^{SM} = f_B \frac{g^2}{8m_W^2} V_{ub}^* \bar{\nu} \not{P}(1 - \gamma_5) l. \quad (11)$$

So the branching ratio in $B^+ \rightarrow l^+ \nu$ is, by using eqs. (9), (11),

$$\begin{aligned} \text{Br}(B^+ \rightarrow l^+ \nu) &= \tau_B \frac{p_c}{8\pi m_B^2} \Sigma_\lambda |A^U + A^{SM}|^2 \\ &= \text{Br}(B^+ \rightarrow l^+ \nu)^{SM} |1 + r e^{-i(\phi_w + \phi_U)}|^2 \end{aligned} \quad (12)$$

where

$$\text{Br}(B^+ \rightarrow l^+ \nu)^{SM} = \frac{G_F^2 m_B m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_B^2}\right)^2 \tau_B f_B^2 |V_{ub}|^2 \quad (13)$$

is the branching ratio in SM,

$$r = \frac{8 C_S^l C_S^{bu}}{g^2 |V_{ub}|} \frac{A_{d_U}}{2 \sin(d_U \pi)} \frac{(m_B^2)^{d_U-1} m_W^2}{\Lambda^{2d_U}} \left(1 - \frac{\mu^2}{m_B^2}\right)^{d_U-2} \quad (14)$$

with $V_{ub} = |V_{ub}| e^{-i\phi_w}$ and ϕ_w is the angle γ of the unitarity triangle, $\gamma = 77_{-32}^{+30}^\circ$ (CKMfitter) [43] and $\gamma = 88 \pm 16^\circ$ (UTfit) [44], which we use $\gamma = 80^\circ$ in the numerical studies. We define the Br of $B \rightarrow l \nu$ as the average of $\text{Br}(B^- \rightarrow l^- \bar{\nu})$ and $\text{Br}(B^+ \rightarrow l^+ \nu)$. In eq.(12), ϕ_w is the weak phase from the CKM matrix element and the phase ϕ_U comes from the propagator of unparticle and is CP conserved, like the strong phase in QCD. As emphasized in ref. [4, 5], the existence of ϕ_U is an unusual feature in unparticle physics. A non-zero ϕ_U leads to direct CP violation in $B^\pm \rightarrow l^\pm \nu$:

$$\begin{aligned} A_{\text{CP}} &\equiv \frac{\Gamma(B^- \rightarrow l^- \bar{\nu}) - \Gamma(B^+ \rightarrow l^+ \nu)}{\Gamma(B^- \rightarrow l^- \bar{\nu}) + \Gamma(B^+ \rightarrow l^+ \nu)} \\ &= \frac{2r \sin \phi_U \sin \phi_w}{1 + r^2 + 2r \cos \phi_U \cos \phi_w} \end{aligned} \quad (15)$$

In the above calculations we have assumed the vector unparticle is transverse, like the vector particles in SM. However, it could contain the longitudinal component because we do not know its properties at present. We now discuss the contribution of the longitudinal component to the branching ratio and direct CP violation in the decays $B^\pm \rightarrow l^\pm \nu$. Setting $\Pi_{\mu\nu} = P_\mu P_\nu / P^2$ in eq. (7), we obtain

$$A_{\text{long}}^U = \frac{C_V^l C_V^{bu}}{C_S^l C_S^{bu}} \frac{\Lambda^2}{m_B^2} A^U \quad (16)$$

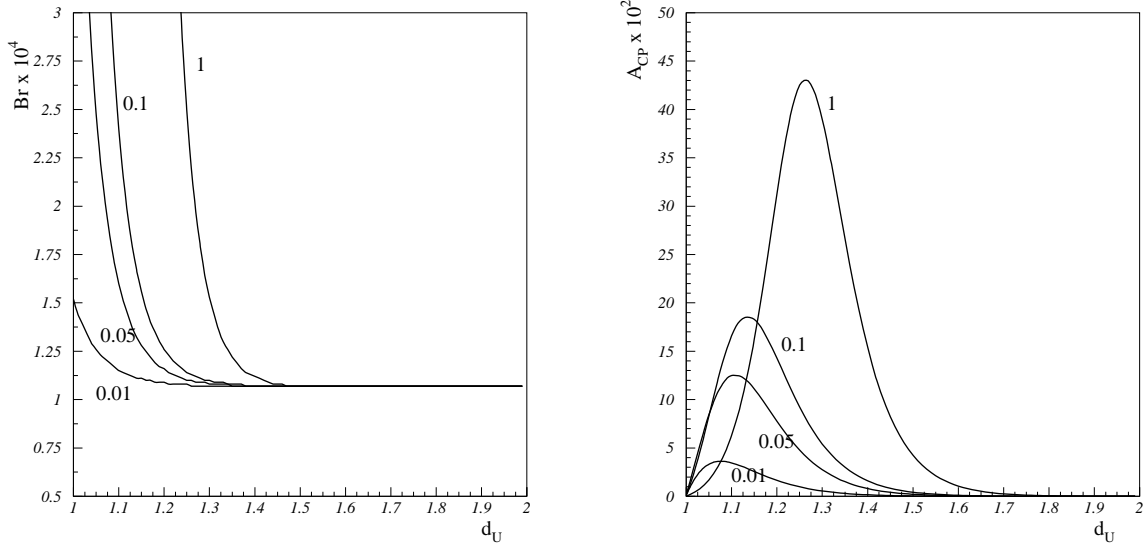


FIG. 1: Scalar unparticle contribution to Br and A_{CP} of $B^- \rightarrow \tau \bar{\nu}$. From right to left, the corresponding coefficients are $C_S^{bu} C_S^l = 1., 0.1, 0.05, 0.01$.

where A^U is the contribution of unparticles to the decay amplitude due to scalar unparticles, eq. (9). Therefore, the contribution of longitudinal component dominates that of scalar unparticle by a factor of $(\Lambda/m_B)^2$ if the coupling constants of vector unparticle are in the same order as those of scalar unparticle in magnitude. The Br of $B^\pm \rightarrow l^\pm \nu$ will constrain the parameters, $C_V^l C_V^{bu}$ or Λ and d_U strongly, which we shall discuss below.

In numerical calculations we fix $\Lambda = 1$ TeV and first consider the case of scalar unparticle. In Fig. (1), we plot the dependence of Br and A_{CP} as a function of scaling dimension d_U , for different multiplicity of $C_S^{bu} C_S^l = 1.0, 0.1, 0.05, 0.01$, with $\mu = 0$. For $C_S^{bu} C_S^l = 0.01$, the unparticle contribution is quite small. However, in the case of $C_S^{bu} C_S^l = 1$, the contribution is large, the Br exceeds experimental bound when $d_U \leq 1.3$, and A_{CP} can reach 30% under the Br constraint. We estimate the effects of the infra-red cutoff by taking $\mu = 0.5 m_B$ and the effects are quit small.

In Fig.(2), we study the contribution of longitudinal vector unparticle to Br and A_{CP} of $B^\pm \rightarrow \tau^\pm \nu(\bar{\nu})$, and include the constraint from the Br when we consider the theoretical maximum of A_{CP} . We plot the Br and A_{CP} as a function of d_U with different parameters of $C_V^q C_V^l = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}$. We find A_{CP} can be as large as 100% with $C_V^q C_V^l = 10^{-2}$, even under the constraint of the Br . The reason is that r (see eq. (14) for its definition) can reach 1 due to the enhancement of $(\Lambda/m_B)^2$ (see eq.(16)). When $C_V^q C_V^l = 10^{-6}$, the maximum of A_{CP} can be 10% under the constraint of the Br .

To see the possible effects of unparticles we should impose constraints from precisely measured QED processes. The contributions of charged unparticles to Bhabha scattering arise at the loop level and consequently are small compared with those at the tree level, such as the νe scattering. Because there is no data of $\nu \tau$ scattering we assume unparticle-leptons coupling universality to proceed. The interaction in eq.(5) contributes to $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$

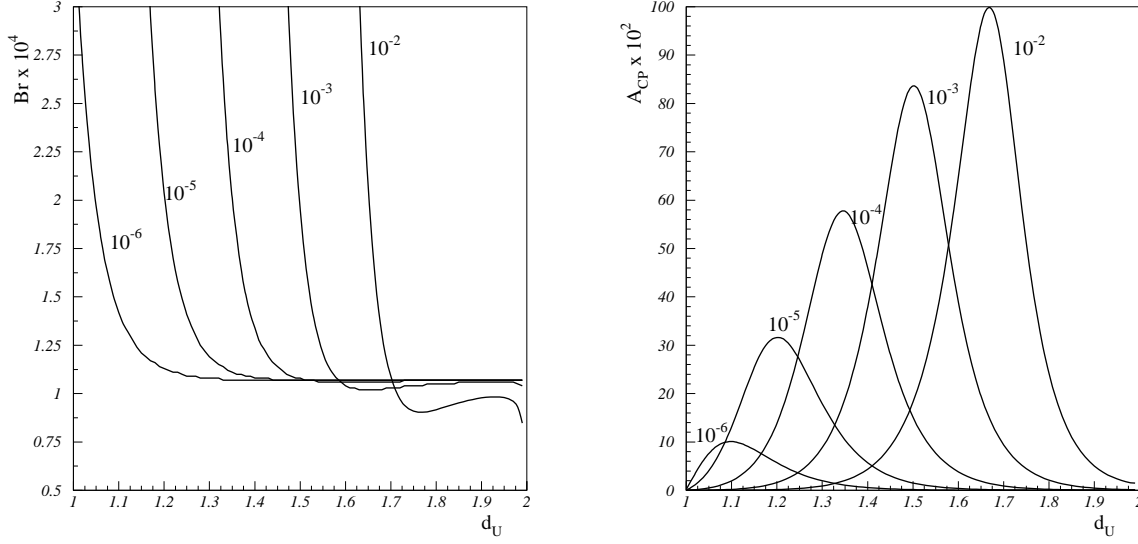


FIG. 2: Longitudinal vector unparticle contribution to Br and A_{CP} of $B^- \rightarrow \tau \bar{\nu}$. From right to left, the corresponding coefficients are $C_V^{bu} C_V^l = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}$.

elastic scattering through s-channel charged unparticle[†]. For the contribution of scalar unparticle, the differential cross section is straightforwardly calculated and the result is

$$\frac{d\sigma}{dT} = \left| \frac{A_{dU}}{2 \sin(d_U \pi)} \right|^2 |C_S^l C_S^l|^2 \frac{m_e^5}{2\pi} \frac{s^{2d_U-4}}{\Lambda^{4d_U}}. \quad (17)$$

The contribution from vector unparticle can be written as

$$\frac{d\sigma}{dT} = \left| \frac{A_{dU}}{2 \sin(d_U \pi)} \right|^2 |C_V^l C_V^l|^2 \frac{m_e}{\pi(s - m_e^2)^2} (s + t - m_e^2)^2 \frac{s^{2d_U-4}}{\Lambda^{4d_U-4}}, \quad (18)$$

where the terms proportional to m_e^5 have been neglected. In above two equations T is the energy of the recoil electron and s, t, u are the Mandelstam variables, which are a function of incoming neutrino energy E_ν .

We now consider the constraint on unparticle-lepton couplings from the TEXONO experiment searching for the neutrino magnetic moments [40]. In the case of scalar unparticle, there are essentially no constraints on the parameter space, because of the m_e^5 factor in the cross section of $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$ scattering in eq.(17). In the vector unparticle exchange in $\bar{\nu}_e e$ scattering, d_U are constrained to be larger than 1.5329, 1.3882, 1.2453, 1.1034 for different $C_V^{bu} C_V^l = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$, respectively. When $C_V^{bu} C_V^l = 10^{-6}$, the constraint on d_U is very small. We find that A_{CP} can still reach their peak value shown in Fig. (2) under the constraint.

If we further assume both unparticle-lepton coupling universality and unparticle-quark coupling universality, the interactions in eq.(5) and (6) also contribute to the $\pi^- \rightarrow \mu \bar{\nu}_\mu$ decay channel. The constraint on unparticle couplings arising from the decay is quit stringent. In the case of scalar unparticle, d_U are constrained to be larger

[†] The contributions of SM singlet unparticles to the scattering, which arise through t-channel unparticle exchange, have been investigated in ref. [39].

than 1.4550, 1.3882, 1.3643, 1.3045 for different $C_S^{bu}C_S^l = 1., 0.1, 0.05, 0.01$, respectively. When $C_S^{bu}C_S^l = 1.$, A_{CP} is bound to be smaller than 8%, while when $C_S^{bu}C_S^l = 0.1, 0.05, 0.01$, A_{CP} is smaller than 2%. In the case of longitudinal vector unparticle, the constraint from $Br(\pi^- \rightarrow \mu\bar{\nu}_\mu)$ is even more stringent. A_{CP} is smaller than 1%, when $C_V^{bu}C_V^l$ takes values as in Fig.(2) and $d_U < 2$.

We know from the table 1 in ref. [42] that SuperB factories will at best be able to measure the branching ratio of $B \rightarrow \tau\nu$ at a 5% level, which would make a measurement of CP asymmetry at 8% almost impossible. However, from our understanding on quarks so far, it is expected that the universality of unparticle-quark coupling could be violated significantly, in particular, for the third generation. Therefore, the stringent constraint from the $Br(\pi^- \rightarrow \mu\bar{\nu}_\mu)$ may not be applicable to the B decay $B^\pm \rightarrow \tau\nu$ and consequently the CP asymmetry of $B \rightarrow \tau\nu$ can be large enough to be measured, as shown above. In this case it is also interesting to measure the direct CP violation in $B \rightarrow \mu\nu$ since B factories have a better identification for μ than that for τ . It is obvious from eqs.(14), (15) that A_{CP} 's are the same for $l = e, \mu, \tau$ if the couplings $C_{S,V}^l$ for $l = e, \mu, \tau$ are the same while the branching ratio of $B \rightarrow \tau\nu$ has a enhancement of order of 100 than that for $B \rightarrow \mu\nu$ due to $m_\tau \doteq 17 m_\mu$.

In summary, we have calculated the effects of unparticles in the decays $B^\pm \rightarrow l^\pm\nu$. We have estimated the effects of scale invariance breaking on Br and CP violation, which is due to the interaction of electromagnetically charged unparticles with SM particles, and the result is that effects are not significant in general. It is found that the direct CP violation in $B \rightarrow l\nu$, which is zero in SM and all other well-known models so far, can reach 30% for scalar unparticle contribution, and 100% for longitudinal vector unparticle contribution under the constraints of $Br(B \rightarrow \tau\nu)$ and νe elastic scattering. However, if the universality for both unparticle-lepton and unparticle-quark couplings is assumed, the direct CP violation in $B \rightarrow l\nu$ can only reach at most 8% and 1% for scalar and vector unparticles respectively for $d_U < 2$ due to the constraint from the decay $\pi^- \rightarrow \mu\bar{\nu}_\mu$. From our understanding on quarks so far, it is expected that the universality of unparticle-quark coupling could be violated significantly, in particular, for the third generation. Therefore, the stringent constraint from the $Br(\pi^- \rightarrow \mu\bar{\nu}_\mu)$ may be not applicable to the B decay $B^\pm \rightarrow \tau\nu$. If the direct CP violation in $B \rightarrow l\nu$ is observed in the future it would give strong evidence for the existence of unparticle stuff.

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